FINAL REPORT

YBCO Coated Conductor Development by Non-Vacuum Chemical Processes

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By
Principal Investigator: Justin Schwartz
Florida State University

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14. ABSTRACT

This report summarizes the research performed under Grant no. F49620-01-1-0381. Additional details of the approach, results and conclusions of the research can be found in the publications resulting from the research, which are listed at the end of this report.

The primary focus of the research was to use magneto optical imaging (MOI) to further our understanding of HTS materials. One particular focus was the use of MOI with in-situ tensile straining to image the effects of mechanical strain on the magnetization, which relates to the current carrying capacity of the conductor. To support the analysis of the MOI imaging, and to convert the results from being qualitative to quantitative, techniques were also developed to interpret the image intensities. Scanning electron microscopy was also used to support the MOI research.

15. SUBJECT TERMS

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Abstract (from proposal)
Weak-link behavior in high-temperature superconductor (HTS) structures is a major impediment for high critical current density (J_c) and is caused by high-angle grain boundaries, as indicated by the absence of biaxial texture. Therefore, novel material processing methods are being explored to increase biaxial texture and J_c for HTS tapes. Ion-Beam Assisted Deposition (IBAD) methods have been successfully applied to fabricate one-meter length superconductor tape with high J_c. The Rolling Assisted Biaxially Textured Substrate (RABiTS^{tm}) method is another means of achieving superconductor texture by a bulk recrystallization process. Recently, Inclined Substrate Deposition (ISD) has been explored as a rapid deposition technique for biaxially oriented buffer layers on polycrystalline metal substrates. All of these techniques have the potential to produce biaxial texture in long-length HTS tape. Understanding the differences between these approaches at the microstructural level, including the interplay between microstructure and electromagnetic properties, is critical to the ultimate development of a technical conductor.

A technologically useful conductor in long lengths will only become viable if the fundamental issues that limit the thickness and length of high quality HTS are understood. Here we propose extensive microstructural characterization of the substrates, buffer layers, and HTS layer, and the interfaces between them. We also propose thorough magnetic and electrical characterization that will facilitate direct correlation between microstructure and properties. A new magneto optical strain imaging system (MOSIS) is the focal point of the proposed research. This new system facilitates simultaneous, real-time observation of the electromagnetic properties and microstructure of the HTS layer. Scanning electron microscopy (with an *in-situ* strain stage) and scanning transmission electron microscopy will facilitate probing the micromechanical behavior at higher resolution. Extensive measurements of J_c, by transport and magnetization, and as a function of magnetic field, temperature, and mechanical strain, will be routine in the evaluation of HTS coated conductors and support the MOSIS studies. Through these studies we will more fully explore the relationships between microstructure, micromechanics, and superconducting properties, and thus address the key scientific issues that presently limit the length and thickness of high J_c coated conductors.

Introduction
This report summarizes the research performed under Grant no. F49620-01-1-0381. Additional details of the approach, results and conclusions of the research can be found in the publications resulting from the research, which are listed at the end of this report.

The primary focus of the research was to use magneto optical imaging (MOI) to further our understanding of HTS materials. One particular focus was the use of MOI with *in-situ* tensile straining to image the effects of mechanical strain on the magnetization, which relates to the current carrying capacity of the conductor. To support the analysis of the MOI imaging, and to convert the results from being qualitative to quantitative, techniques were also developed to interpret the image intensities. Scanning electron microscopy was also used to support the MOI research.

The primary focus of the research was on Y-Ba-Cu-O superconductor; some studies were also performed on Bi-Sr-Ca-Cu-O, Tl-Ba-Ca-Cu-O and Hg-Ba-Ca-Cu-O. Samples were received from industry, national laboratories, other universities and grown locally at FSU.

<u>Magneto Optical Imaging with Strain</u>

Figure 1 shows a photograph of the MOI system with the straining device and all necessary components. As shown, the cryostat is open, with the lid visible in the rear of the photograph. Figure 2 shows an enlarged view of just the straining system.

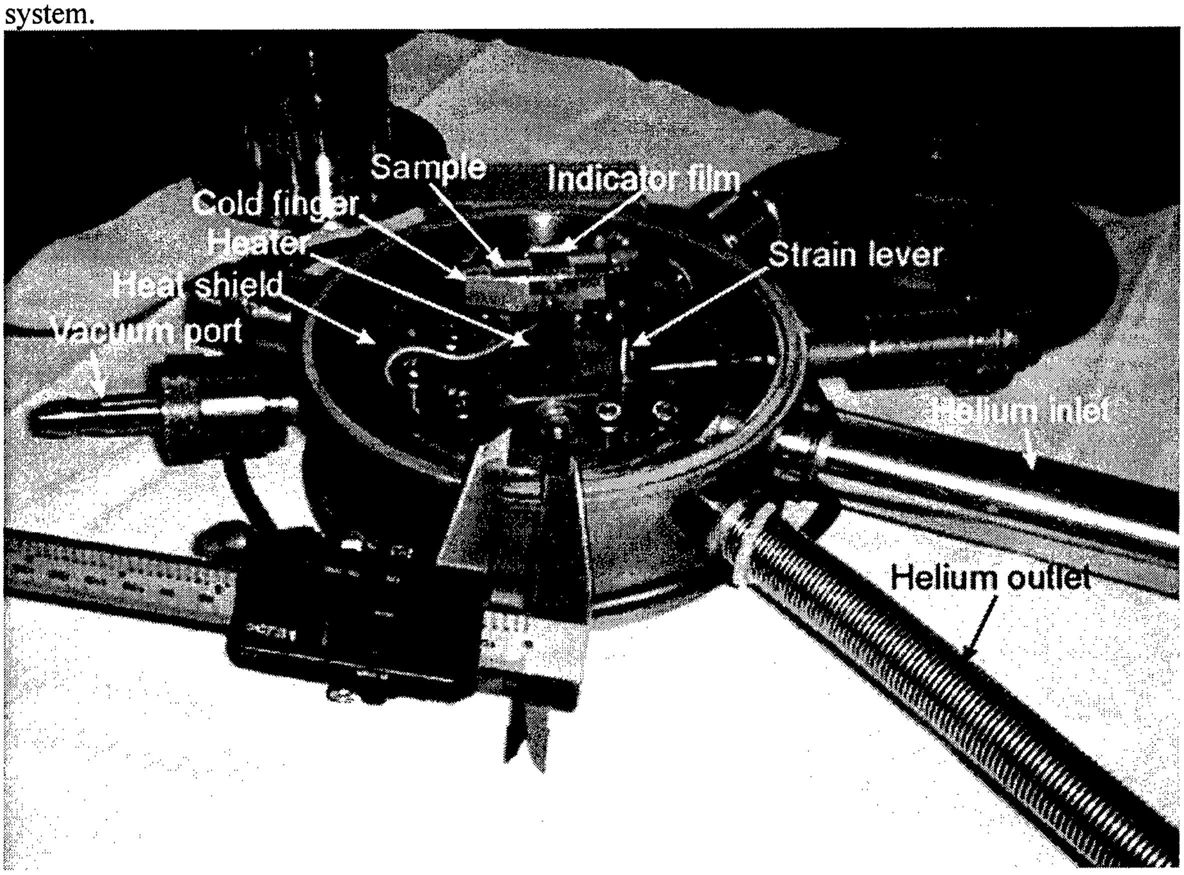

Figure 1: Photograph of the magneto optic strain imaging system (open to show inner components; microscope not shown).

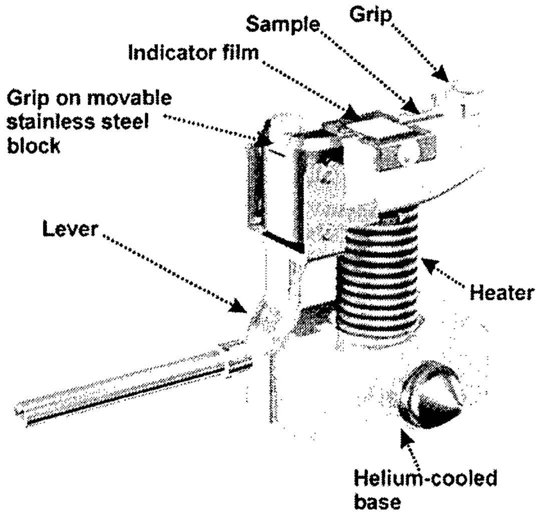

Figure 2. Strain is applied to the sample by moving the grips apart by use of a lever.

Experimental Samples

Experimental samples have been received from a number of collaborators. These include:

- $Bi_2Sr_2Ca_2Cu_3O_x$ manufactured by American Superconductor Corporation, obtained via the University of Twente.
- $Hg_2Ba_2Ca_2Cu_3O_x$ grown by J. Wu, University of Kansas, and internally at FSU by J. Su.
- $Tl_2Ba_2CaCu_2O_x$ grown by Lincoln Labs.
- $YBa_2Cu_3O_{7-\delta}$ from the Air Force Research Laboratory, Oak Ridge National Laboratory and American Superconductor Corporation.

Results: Experimental

Results for the various experiments and summarized here.

$Bi_2Sr_2Ca_2Cu_3O_x$ (BSCCO) samples were primarily used in the beginning of the project to develop and refine the MOI with strain technique. At this time, high quality $YBa_2Cu_3O_{7-\delta}$ (YBCO) samples were still somewhat scarce, while BSCCO samples were plentiful. Figure 3 shows a BSCCO sample etched on one side to expose the superconducting filaments, reinforced to ensure that the region of interest (ROI) is that which fails first, and instrumented with a strain gauge to quantify the level of strain applied. Figure 4 shows MOI images of the sample before straining and after applying

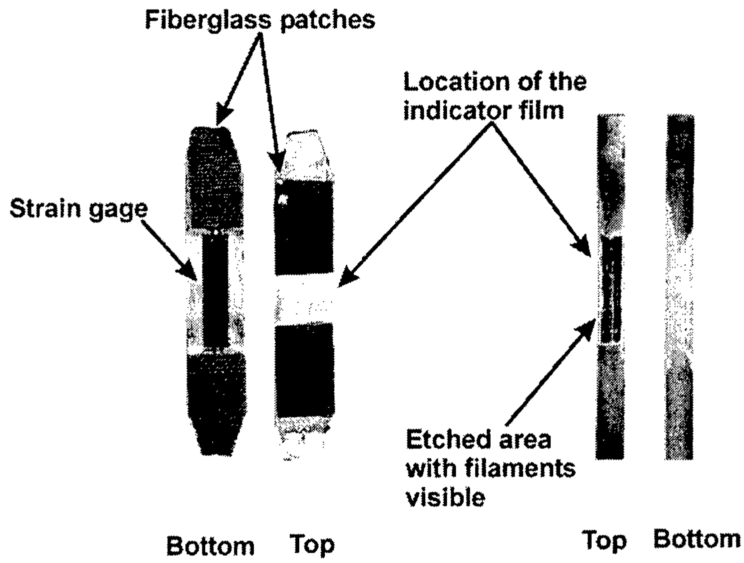

Figure 3. BSCCO sample prepared for MOI with strain.

the maximum strain applied (multiple intermediate straining steps are not shown). In the strained sample, one can see numerous cracks that jump from filament (bright yellow – indicating trapped magnetic flux) to filament. In one location, one sees where the crack has not fully propagated across the sample.

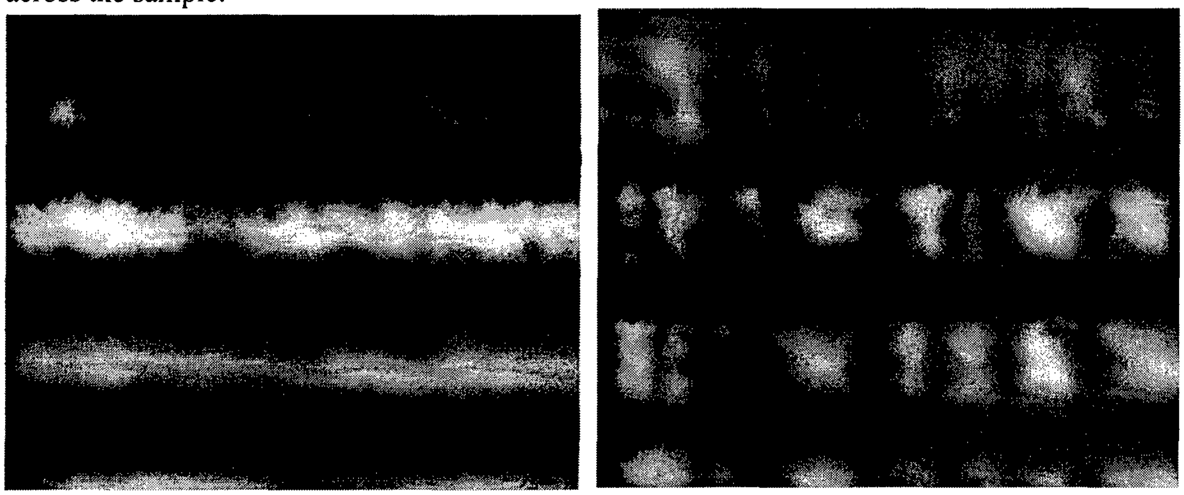

Figure 4. MOI with and without strain of the BSCCO sample, showing crack growth.

Figure 5 shows three MOI images of a YBCO coated conductor: zero strain (top), some strain (middle) and additional strain (bottom). Figure 6 shows the corresponding SEM image of the sample. Note the vertical striations in the MOI image after strain has been applied. These striations, which correspond to cracking in the conductor, do not correlate with the YBCO grain structure. Instead, it is believed that the failure correlates with the grain structure of the underlying Ni substrate. Note also in the SEM that the Ag coating applied atop the YBCO layer has no impact on arresting crack development.

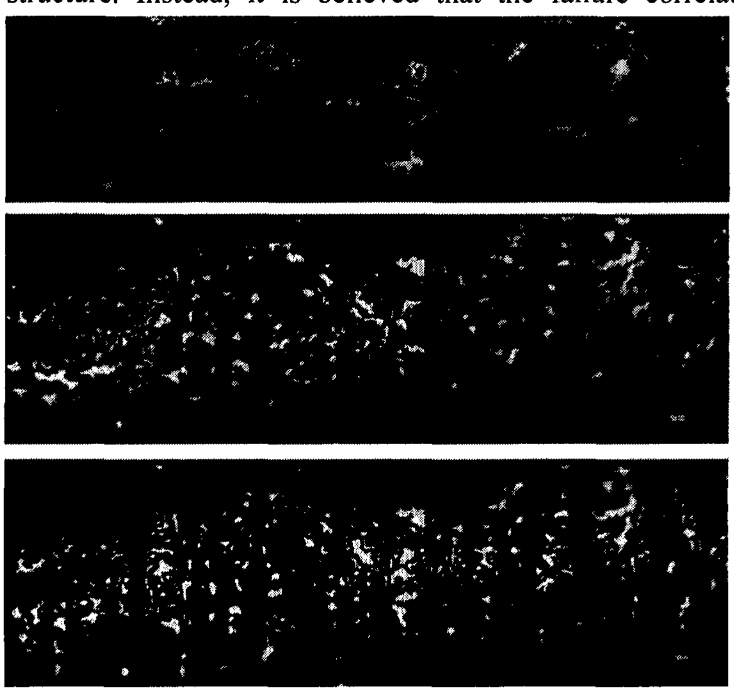

Figure 5. MOI with and without strain of theYBCO sample, showing crack growth.

Figure 7 compares two MOI images of different locations in a YBCO coated conductor with a transport critical current versus location plot obtained at the University of Twente using a "magnetic knife" which isolates regions of a conductor by applying a nil magnetic field to the ROI and a large magnetic field to the

remainder of the conductor. Illustrated in this figure is that the MOI image null points correlate well with regions that have zero transport critical current.

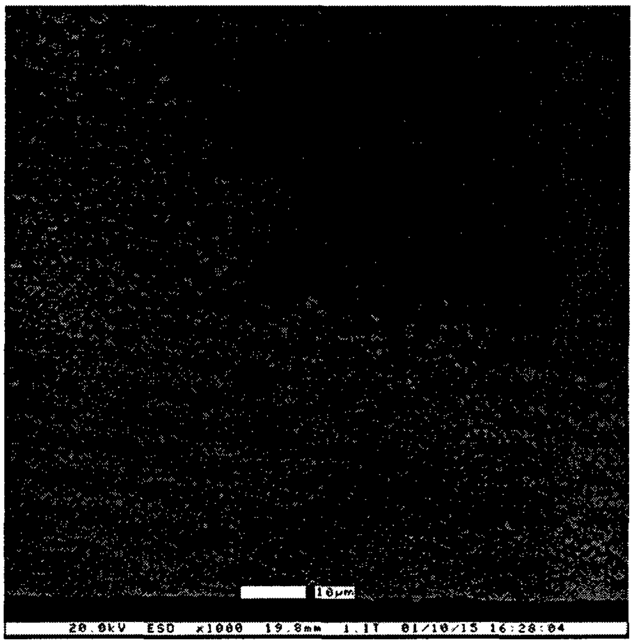

Figure 6. SEM after straining of the YBCO sample shown in Figure 5, showing crack growth.

Results: Computational

Computational results were obtained by applying the theoretical work of Baziljevich *et al.*, Kadowaki *et al.*, and De Vries *et al.* In particular, annihilation theory and curl calculations were was used to determine two-dimensional critical current density distributions from MOI images. Typical results are seen in figure 8, which shows an MOI image at 50 K, 90mT for a YBCO coated conductor, and the corresponding current density distribution.

Advanced degrees resulting from this project

Daniel C. van der Laan, Ph.D., 2004. Currently a post-doctoral researcher at NIST-Boulder.

Publications resulting from this project

1. D.C. van der Laan, M.W. Davidson, B. ten Haken, H.H.J. ten Kate, and J. Schwartz, "Magneto-Optical Imaging study of the crack formation in superconducting tapes caused by applied strain," *Physica C* **372-376** 1020-1023 (2002)
2. D.C van der Laan, H.J.N. van Eck, B. ten Haken, H.H.J. ten Kate, and J. Schwartz, "Strain Effects in High Temperature Superconductors Investigated with Magneto-Optical Imaging," *IEEE Transactions on Applied Superconductivity* **13**(2) 3534-3539 (2003)
3. I.B. Rutel, C. McIntosh, A. Caruso, M.W. Davidson and J. Schwartz, "Quantitative analysis of current density distributions from magneto-optical images of superconducting $YBa_2Cu_3O_{7-\delta}$ coated conductors," *Superconductor Science and Technology* 17 S269-S273 (2004)
4. I.B. Rutel, C. McIntosh, A. Caruso, D.C. van der Laan, M. Davidson, and J. Schwartz, "Magneto optical imaging of crackingin high temperature superconducting thin films and tapes under tensile strain," in Magneto Optical Imaging, NATO Science Seriew, II. Mathematics, Physics and Chemistry – Vol. 142, 133-140, T.H. Johansen and D.V. Shantsev, eds. (2004)
5. D.C. van der Laan, "Flux pinning and connectivity in polycrystalline high-temperature superconductors," Ph.D. Dissertation, University of Twente, Netherlands (2004)
6. D.C. van der Laan, L.M. Naveira, H.J.N. van Eck M. Dhalle, B. Metz, J. Schwartz, M.W. Davidson, B. ten Haken and H.H.J. ten Kate, "Direct experimental analysis of the relation between the grain structure and distribution in critical current density in $YBa_2Cu_3O_{7-\delta}$ coated conductors," *Superconductor Science and Technology* **18** 299-306 (2005)

7. D.C. van der Laan, H.J.N. van Eck, M. Dhalle, B. Metz, B. ten Haken, H.H.J. ten Kate, L.M. Naveira, M.W. Davidson and J. Schwartz, "Current distribution and grain connectivity in $YBa_2Cu_3O_{7-\delta}$ coated conductors," *Applied Physics Letters* **86** 032512-1:3 (2005)
8. J. Wu, D.C. van der Laan, and J. Schwartz, in preparation (a manuscript on the Hg-CC research at U. Kansas, including some MOI images done at FSU).

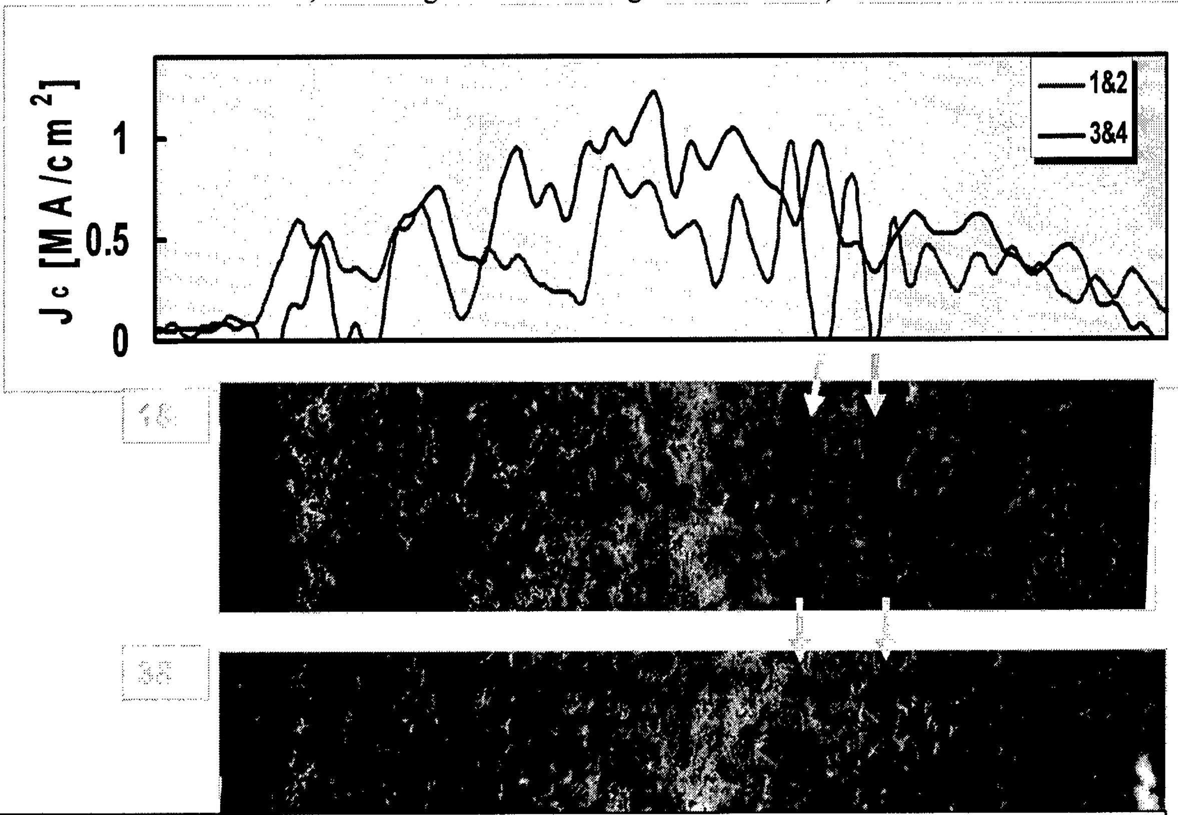

Figure 7. Magnetic knife profile of critical current density versus location, and corresponding MOI images. Both are taken after straining the YBCO coated conductor.

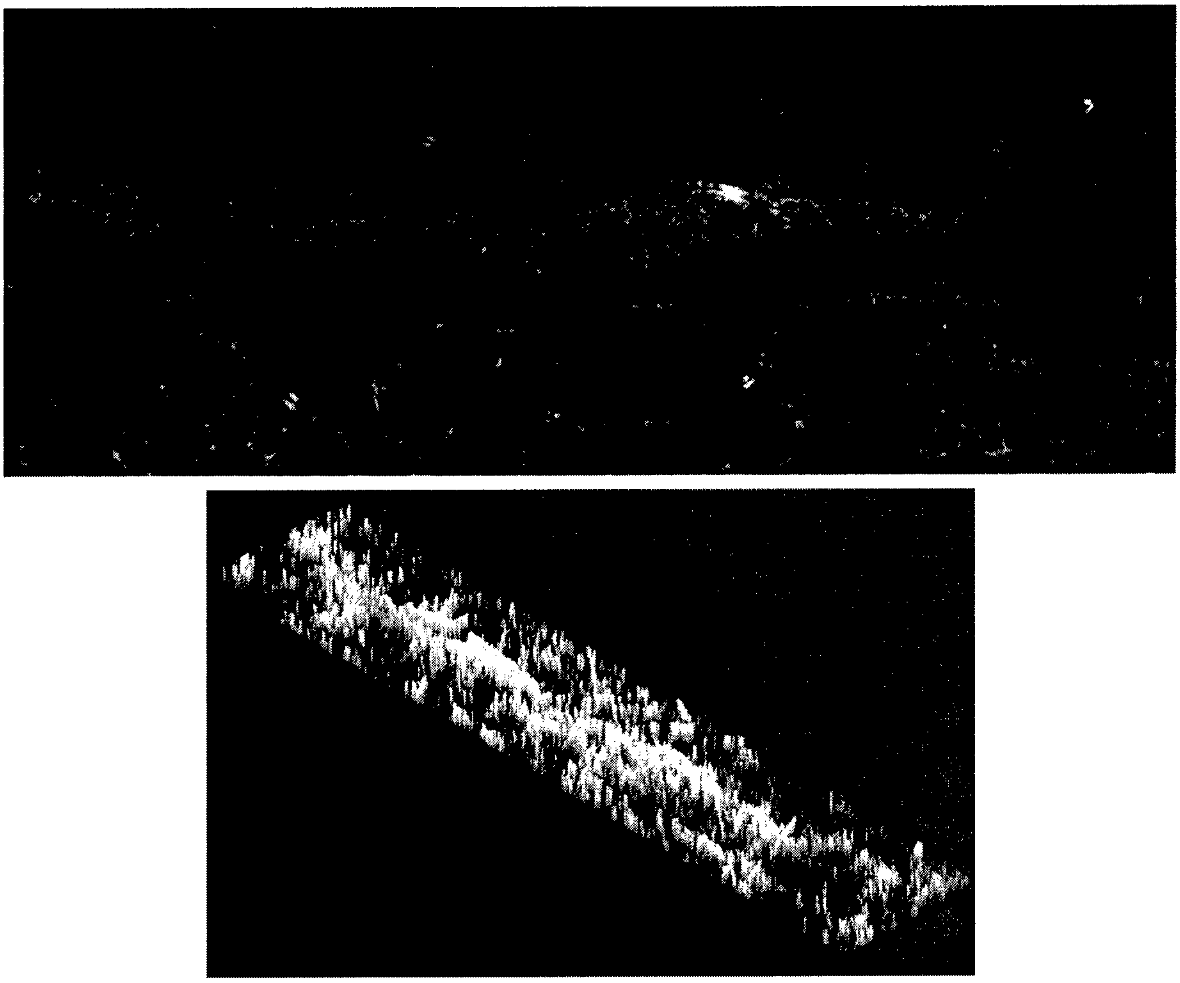

Figure 8. MOI image of a YBCO coated conductor at 50 K, and the corresponding two-dimensional critical current density profile.